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STUDY OF ELECTRO-MAGNETIC PROPAGATION OF A TRANSIENT SIGNAL THROUGH SEA WATER

By

M. J. Larsen
C. R. Gano
M. M. Newman

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ABSTRACT

Reported are results of air-to-undersea transmission of a high-power pulse signal. A signal was produced by discharging a capacitor bank into a kite-supported antenna of lengths on the order of 3,000 feet. Signals were received by a loop antenna at a distance of approximately one nautical mile. Data were obtained for reception on the surface and at loop depths of five feet and ten feet. The results are compared with theoretical expectations using normal sea water conductivity values. Included is an expression for optimum propagation frequency as a function of ocean depth for loop antenna reception. Comment is made on the interface problem.

INTRODUCTION

In an earlier study[1] the experimental results of electromagnetic propagation of a high-power transient wave in sea water were reported. The transmitting source was a large square loop, 11 feet on a side, which was energized by the discharge of a capacitor bank. The receiver was a smaller loop which fed into an oscilloscope. The distances concerned were usually less than 250 meters, but the depths approached 30 meters. As the frequency spectrum of the transmitting pulse centered around 500 cps, the distances were well within the induction field range. Even so, the results pointed out that if the surface field strength were established, then the underwater strength could be determined as a function of the depth, frequency, and water properties. It was desired, however, to explore pulse propagation characteristics at frequencies extending more into the radiation field range, thus requiring greater distances and a somewhat higher frequency spectrum.

In order to radiate pulses substantial distances, a large helicopter-supported wire has been used successfully by Lightning and Transients Research Institute on a number of experiments.[2]

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[1]Technical Report No. 1, "Study of Electro-Magnetic Propagation of a Transient Signal Through Sea Water", by M. J. Larsen, M. H. Latour and M. M. Newman, Contract No. Nonr 580(10), April 1961.

[2]See, for example, "Sea-Going Lightning Generator", by Newman, Stahmann and Robb, Electronics, July 1960.

As preliminary tests with kites designed for the purpose[3] indicated considerable promise at much less expense, arrangements were made to go ahead with a kite-supported antenna. The possibility of obtaining air clearance off the coast of Florida for any extended periods of time became nil. As we had conducted a number of projects previously in the Bahamian Island area, we explored the possibilities there. With the generous cooperation of the Bahamian Government officials, air clearance was granted for operations in and around South Bight of Andros Island for the period April 10 to 20, inclusive, 1962. This work was done with the collaboration of Lightning and Transient Research Institute, with the aid of their research schooner, Azara, and personnel. The Azara moved from Florida to South Bight after we made final arrangements with the Bahamian Government in Nassau. At first, the sea was too rough to leave the Florida coast and then, after arriving and anchoring in South Bight, the normally strong prevailing southeastern winds shifted to the northeast and were adequate for supporting the antenna for only a few days during the 11-day period.

For the receiving equipment the original plan was to record the signals on a tape recorder housed in an aluminum sphere with cross-loop antennas, as shown in Figs. 1 and 2. The tape recorder was a two-channel model operated by an inverter. As the waves in the deep water outside of South Bight (on the southeastern coast of Andros Island) were excessively high for handling the

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[3]Patrick Ellam, Inc., Mamaroneck, N.Y.

sphere assembly with the smaller fishing sailing vessel rented locally at Lisbon Creek, all work was conducted in the extensive, but protective area of South Bight. This area has a coral bottom and is quite shallow, averaging between 8 and 10 feet deep over many square miles. There was a hole about a mile from where the Azara was anchored, however, which rounded down to over thirty feet in depth, with a diameter of some two hundred feet. This was used as the major receiving base. A rough sketch of the relative location of the Azara and receiving vessel is indicated in Fig. 3.

The procedure first attempted was to assemble the equipment and close the sphere on board the Azara. Then the assembly was lowered with a small raft float and towed to the receiving boat as shown in Fig. 4. When in place at the receiving location, the tape starting relay was tripped by removing a cord connected externally which left the assembly completely isolated electrically from the surface. A depth gauge was also included in the sphere assembly. On the first two attempts, despite much prior testing at Daytona Beach and in the laboratories, trouble developed in the tripping circuit, and also with the tape reels. When all these troubles were resolved, the wind was not strong enough for the kite to support a sufficient length of wire. As the upper frequency limit of the tape recorder was 30,000 cps, it was necessary to have the kite length exceed the one-quarter wavelength for this frequency. This was $3 \times 10^8/(4)(30{,}000)$, or over 2,500 meters, if an appreciable portion of the pulse spectrum were to be received.

We also had an interest, however, in making measurements with a non-isolated loop. It was determined to take readings with the receiving loop alternately in a plane parallel to the assumed direction of the incident wave, and then perpendicular to the incident wave. Then, if appreciable differences in readings were observable, it would be established that the signals were substantially loop induced and not an unbalanced whip-antenna component. As a result, the more significant data reported herein were taken from a loop with attached cable leading to the receiving equipment housed on the boat at the receiving location. The remainder of the Report discusses further the equipment, procedures, data, and results obtained while using this loop.

THE ENERGY SOURCE AND ANTENNA

The capacitor bank in the Schooner Azara was made up essentially of 15 capacitors of 1/2 microfarad capacitance each and 15 capacitors of 3/4 microfarad capacitance each. These were all charged in parallel to approximately 27 KV and then discharged in series into the antenna and a load resistance of 6,000 ohms. Thus, the discharge circuit consisted of an equivalent 0.02 microfarad capacitance charged to 30 times 27,000, or 810,000 volts. The total energy released through discharge is approximately 6,560 joules. The equivalent discharging circuit is shown in Fig. 5. The 6,000-ohm resistance in the discharge circuit is the resultant series resistance of 60 charging resistors of 400 ohms each placed in pairs between the capacitors when in parallel charging array. Input currents were recorded oscillographically by tapping off the 0.005-ohm shunt.

The antenna wire consisted of seven strands of No. 26 copper-weld to give adequate tensile strength to withstand the variable stress from the kite. The tension was maintained relatively uniform through a controlled torque reel placed just above the capacitor bank in the center of the bronze-hulled schooner. The wire was played out through a swivel pulley supported between the tops of two masts. The kite was of a design worked out by

Ellam.[3] Although support of shorter lengths was possible with winds of velocity as low as 10 knots, a velocity in excess of 14 knots was needed for reliable support for longer lengths, up to 3,000 and more feet. With higher wind velocities, elevations approaching 70 degrees from horizontal were attainable. For this work reported herein, the wind velocity was adequate for a wire length of approximately 3,000 feet. The wire would hang in a catenary shape with the bottom of the sag maintained well above the water surface during all discharge periods.

As the use of kites for this type of work shows promise, a few further words may be in order about the techniques employed in the Andros Island area. A trip mechanism was employed as a safeguard should some uninformed aircraft come dangerously close. Should the wire break near the reel, there was always the possibility that the kite would stay aloft trailing a length of wire for some considerable distance. The trip was near the kite so that the wire could drop and be reeled in quickly. The kite was launched by taking it some 100 yards from the Azara in a small boat and then releasing when sufficient torque was indicated on the reel. (See Fig. 6.) When the wind was slack the reel would take in wire, and conversely when the wind increased. Wire-length records were kept for correlating with transmitting and receiving signals.

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[3] loc. cit.

RECEIVING EQUIPMENT

The receiving equipment consisted of a 20-turn loop; see Fig. 7. The loop had an open shield connected at the neck to a support pipe through which passed two shielded cables leading to the oscilloscope. The shields of the cables were connected to the pipe at the furthermost extremity. The entire input circuit was balanced so that any signals other than those induced in the loop would be reduced to a minimum. The loop circuit constants were such that with suitable termination resistance the terminal voltage was substantially the same as the induced voltage up to a signal frequency of 100 kc. As 100 kc was the approximate resonant frequency of the loop with leads, there was rapid attenuation above 100 kc, the Q with load being on the order of unity at resonance. The schematic circuit is shown in Fig. 8. Oscillographic records of the received waveforms were made with a Polaroid camera.

TEST PROCEDURE

At the transmitting end the capacitor bank was discharged into the antenna by manual switching. Through radio communication the switching moments were anticipated to allow time to open the camera shutter for oscillographic waveform exposure at the receiving end. The oscilloscope gain was adjusted for each case to produce measurable amplitudes. The loop was positioned for maximum signal with the plane of the loop vertical and in the assumed plane of the incident wave. For minimum signal reception the plane of the loop was vertical and perpendicular to the plane of incidence. Records were taken with the loop on the deck of the receiving vessel, and with the center of the loop underwater at 5-foot and 10-foot depths. As the loop was positioned manually, and as the signal was a transient rather than a continuous wave, it was possible to attain only an approximate minimum position. Although the ocean surface was quite smooth in South Bight, there were some waves and consequently the depth measurements should be considered as having a probable variation of plus or minus one-half foot. In view of these and other variations, such as antenna angle and dip variations, the results accordingly must be interpreted as falling within reasonable limits.

The oscillograms of the signals recorded are shown in Fig. 9. The waveform of the generator current remained substantially uniform throughout the test period. The antenna wire length averaged close to 3,000 feet with but minor variations. The separation distance of the two vessels was calculated as 7,000 feet by reference to navigation charts and by a rough triangulation check.

ANALYSIS OF RESULTS

The loop output of the received signal may be considered a damped sinusoid with a frequency of approximately 80,000 cps. This frequency as measured on the oscillograms corresponds closely with that calculated considering the 3,000-foot antenna as one-quarter wavelength. It would be expected that the loop output would have a smooth signal as frequency components above 100,000 cps were attenuated rapidly.

The relation between the magnetic component H of the field and the loop output is readily derivable, as is customary, from Faraday's Law.

$$\oint E \cdot dl = -\frac{\partial}{\partial t} \iint_A B \cdot da$$

which for the amplitude of the induced voltage reduces to

$$V = N\mu H\omega A$$

if H is assumed as the maximum of a sinusoidally varying field of angular frequency ω. With the loop used

$N = 20$ turns

$A = \pi/4$ (The diameter of the loop is 1 meter)

$\omega = 2\pi\ 80,000$

$\mu = 4\pi \times 10^{-7}$

Therefore, the amplitude of the induced voltage becomes

$$V \cong 2\omega H \times 10^{-5} \text{ volts}$$

Although the frequency spectrum of the transmitted wave, being a damped repetitive pulse, is broad, it is assumed as a greatly simplifying measure that the energy is confined to a single sinusoidal signal of approximately 80,000-cycle frequency. On this basis, then, certain calculations can be made more readily. For example, consider the magnetic field strength in air at the receiving terminal as computed from a peak-induced voltage signal of 0.25 volts. From the preceding equation, using $\omega = 2\pi\ 80{,}000$, the value for the magnetic field is

$$H = (V \times 10^5)/2\omega$$
$$= 0.025 \text{ ampere turns/meter}$$

Because of the orientation of the loop this value for H is the horizontal component of the resultant wave, which is the sum of the horizontal components of the incident and reflected waves. As the horizontal components of the incident and reflected waves are in phase the value for H given would be twice the value of H for the incident wave, assuming reflection from a perfect conductor.

Although oscillograms of the electric field were taken with a whip antenna, see Fig. 9, no attempt was made to orient the antenna for maxima or minima outputs, or to calculate electric field intensities. While this would assist in calculating the power density at the particular receiving location, overall power computations, for example, by integrating over a hemisphere centered at the transmitter, would be tedious and subject to large error because of the uncertainty in the precise geometry of the antenna. It may be of incidental interest, however, to compare estimates of the total energy radiated with that stored for a given pulsing sequence.

An approximate radiated energy figure can be calculated by estimating the magnitude of the 80,000-cycle component for each period of the antenna current wave (as if each cycle were withdrawn from one cycle of a continuous wave) and integrating vs. time period by period over the few periods having significant amplitudes. This figure would then be multiplied by the 80,000-cycle radiation resistance of the antenna. Checks taken on a similarly-shaped antenna with scaled-down dimensions at microwave frequencies showed that the order of magnitude of radiation resistance most likely would fall between 5 and 15 ohms depending on the shape of the catenary. By integrating the radiated energy over the discharge period in this manner the value becomes approximately 40 joules assuming the radiation resistance to be a 10-ohm intermediate value. As the total energy released from the capacitor bank during a typical discharge period was 6,560 joules, the energy radiated was very small, about 0.6 per cent. The peak power, even of the estimated 80,000-cycle component, however, was very high, approximately 6.5 megawatts. The radiated energy is low, of course, because the signal is highly damped. Thus over 99 per cent of the stored energy is lost through the charging resistors, the a-c resistance of the antenna wire, and corona.

The horizontal component of the magnetic field at the interface is the same on either immediate side of the boundary.

If H_o is the interface value, then the underwater horizontal component becomes

$$H = H_o \exp(-\alpha z)$$
$$= H_o \exp\left(-\frac{\mu\omega\sigma}{2}\right)^{1/2} z$$

where

α = attenuation constant

z = depth in meters

$\mu = 4\pi \times 10^{-7}$

$\sigma \triangleq 4$ mhos/meter for sea water

Thus

$$H = H_o \exp\left[(-1.58\sqrt{\omega})\ z \times 10^{-3}\right]$$
$$\frac{H}{H_o} = (1.58\sqrt{\omega})\ z \times 10^{-3} \text{ nepers}$$
$$= (0.0137\sqrt{\omega})\ z \text{ db}$$
$$= (0.0342\sqrt{f})\ z \text{ db}$$

The loop output voltages with relative attenuation are shown in the Table. The oscillograms are shown in Fig. 9.

TABLE OF LOOP VOLTAGES AND ATTENUATION

DEPTH	A	B
Surface	0.45V p-p 0 db	0.018V p-p - 29 db
5' Depth	0.021V p-p -27 db	0.0026V p-p -45 db
10' Depth	0.0026V p-p -45 db	0.0014V p-p -50 db

A - Loop in assumed plane of incidence.

B - Loop approximately perpendicular to assumed plane of incidence.

According to the theoretical attenuation, the value at 80,000 kc should be 9.7 db/meter or 3 db/foot. Thus, the 5' depth would be expected to be closer to -15 db and the 10' depth, -30 db in the optimum "A" position. There is considerable departure from the theoretical value. It should be noted, however, that the difference between the 5' and 10' level is 18 db, which corresponds to 3.6 db/foot. To account for the greater discrepancy between the surface and 5-foot depth values, it can be argued that the unsuppressed higher-frequency components of the signal spectrum at the surface add considerably to the surface signal level. But it is not believed that this would completely account for the differences.

A thorough but tedious approach to the problem would be to determine the $H(\omega)$ vs. ω spectrum of the received wave, multiply $H(\omega)$ by $\exp(-\alpha z)$ for the depth concerned and apply the result to the loop.

Referring back to the Table, the readings taken in the approximate minimum position "B" indicate with comforting assurance, because of the marked attenuation compared with the respective "A" positions, that the signals were truly coming from the loop and not from some extraneous unbalanced portion of the circuit. At the 10-foot depth the difference is not great, indicating either some low-level unbalanced signals or a changing orientation of the magnetic component.

The purpose, as mentioned elsewhere, in orienting the loop in maximum and minimum signal positions was to confirm the assumed position of the magnetic vector, as well as to check for unbalanced circuitry. Had the scope been triggered by a direct air signal, further data on delayed transmission through water could have been procured. For the signal frequencies used the group velocity is on the order of 350,000 meters/sec which is a delay of 2.86 microseconds/meter, and easily measurable.

OPTIMUM FREQUENCY FOR A GIVEN DEPTH

For a loop-receiving antenna the output voltage as derived is

$$V = K\omega H_o$$

on the surface, and for depth z

$$V = K\omega H_o \exp(-\alpha z)$$

$$V = K'\omega \exp\left[(-1.58\omega^{1/2})\ z \times 10^{-3}\right] \qquad (1)$$

From the expression (1) it is evident that there is an optimum value of ω for every depth. Thus, differentiating (1) and setting $\frac{dV}{d\omega} = 0$ the result is

$$\omega_1 = 620 \times 10^3/{z_1}^2$$

or

$$f_1 \cong 100 \times 10^3/{z_1}^2 \qquad (2)$$

where z_1, is in meters and f_1 in cycles/sec. The expression (2) is valid, of course, only to the extent that (1) holds, and assuming a loop-receiving antenna. At the 5' depth (1.5 meter), f_1 = 44,000 cps and at the 10' depth (3.05 meters), f_1 = 10,700 cps. At both depths, therefore, the recurrent frequency of the antenna as a quarter wave (80,000 cps) was above the optimum value. The optimum depth for the frequency used would have been 1.12 meters, or approximately 3.7 feet.

The expression for optimum frequency vs. depth admittedly is a simplified expression which was derived for a loop antenna. Much other work has been done along these lines; see, for example, the summary by Hilliard.[4]

[4] E. J. Hilliard, "Getting Signals Through to Submarines", <u>Electronics</u>, Sept. 14, 1962.

COMMENTS ON RESULTANT SIGNALS

The received signal directly measurable near a boundary is the resultant signal and therefore a function of the direction and polarization of the incident wave. The measurements made for the underwater study reported herein were made by a loop antenna and consequently the position and magnitude of the resultant magnetic field vector at the surface are pertinent.

In a vertically-polarized incident wave, for example, the electric vector is in a vertical plane (the plane containing the line between source and receiver), while the magnetic vector is horizontal. It follows that for this case the resultant magnetic vector will be very nearly twice the incident H and substantially independent of the angle of incidence. Thus a loop oriented properly would maintain an output voltage substantially independent of the angle of the incident wave. This is far from true of the resultant electric vector, which varies all the way from twice the incident E down to this maximum multiplied by the intrinsic impedance ratio (η_{sea}/η_{air}) for a wave normal to the surface. Although the resultant electric vector varies widely, the horizontal component of the electric vector remains essentially constant for a given frequency, because the horizontal magnetic vector stays constant. This is because the E and H horizontal components have the intrinsic impedance of sea water as their ratio at the interface.

With horizontal polarization, however, the electric vector is horizontal while the magnetic vector assumes a position within a vertical plane containing the line between source and receiver. The resultant horizontal component of the magnetic vector varies as follows

$$H_{OH} \cong 2H_i \cos\theta$$

where H_i is the incident vector and θ is the angle of incidence with respect to the normal to the surface. It follows also that the resultant electric vector varies as follows

$$E_{OH} \cong 2E_i(\eta_s/\eta_a) \cos\theta$$

where E_i is the incident electric vector and η_s and η_a are the intrinsic impedances of sea and air.

The above discussion leads to approximate results because perfect reflection is inferred when discussing the magnetic vectors and then sea water conditions are used for arriving at horizontal electric components. It would appear, however, that within moderate limits at the lower frequencies for signals gathered by a loop antenna the output at the interface is not a function of the intrinsic impedance of the sea water. For the electric wave, however, the horizontal component is a function of the intrinsic impedance ratio as well as the angle of incidence.

GENERAL REMARKS AND CONCLUSIONS

The original plan for measuring the received transient signal was to employ three mutually perpendicular loops with outputs recorded on magnetic tape. The assembly was to be completely isolated from the surface. No account was to be made of the azimuth of the loops as the magnitude would be the vector sum of three signals in x, y, z quadrature. As only a two-channel recorder was used, the x and y axes were selected, it being assumed that the underwater signal was directed downward normal to the surface. Because of the inability to transmit a signal having major components within the frequency limits of the receiving equipment by the time the equipment was suitably modified, it was necessary to abandon this method. The equipment is available and might well be used in the future, should completely isolated reception be especially desired. Some modification by employing a smaller tape recorder, for example, and a different starting mechanism might be advisable.

The substitution of a single loop with direct connection to the receiving equipment proved, however, to have certain advantages over the proposed isolated-loop method. As mentioned in the report, direct control of the loop position was possible (mainly, of course, because the depths of measurement were not great) thus making possible approximate maxima and minima positions. Furthermore, the direct connection makes possible the measurement of delay time between surface and underwater positions without employing elaborate timing mechanisms. A possible extension of this would be to make simultaneous recordings of the outputs of three cross-loops, using the delay-time measurement as a check on extraneous surface interference.

The results indicate that with the loop oriented for response to the horizontal magnetic component, the approximate underwater transient signal level can be computed in terms of the surface signal level in a simple manner as a function of depth and frequency. With a signal having a vertically-polarized incident wave and the loop oriented in the incident plane, for example, the loop output presumably would be independent at the surface of the angle of incidence (except near 90 degrees), and also independent of the intrinsic impedance of sea water. Thus, the just-above and just-below interface signals would be identical while underwater the loop response would attenuate continuously as a known function of depth and frequency.

Analysis for loop reception indicates that for a constant surface-signal level there is an optimum frequency for a given depth. The optimum frequency is inversely proportional to the square of the depth, limited, of course, by the circuit parameters of the loop and leads.

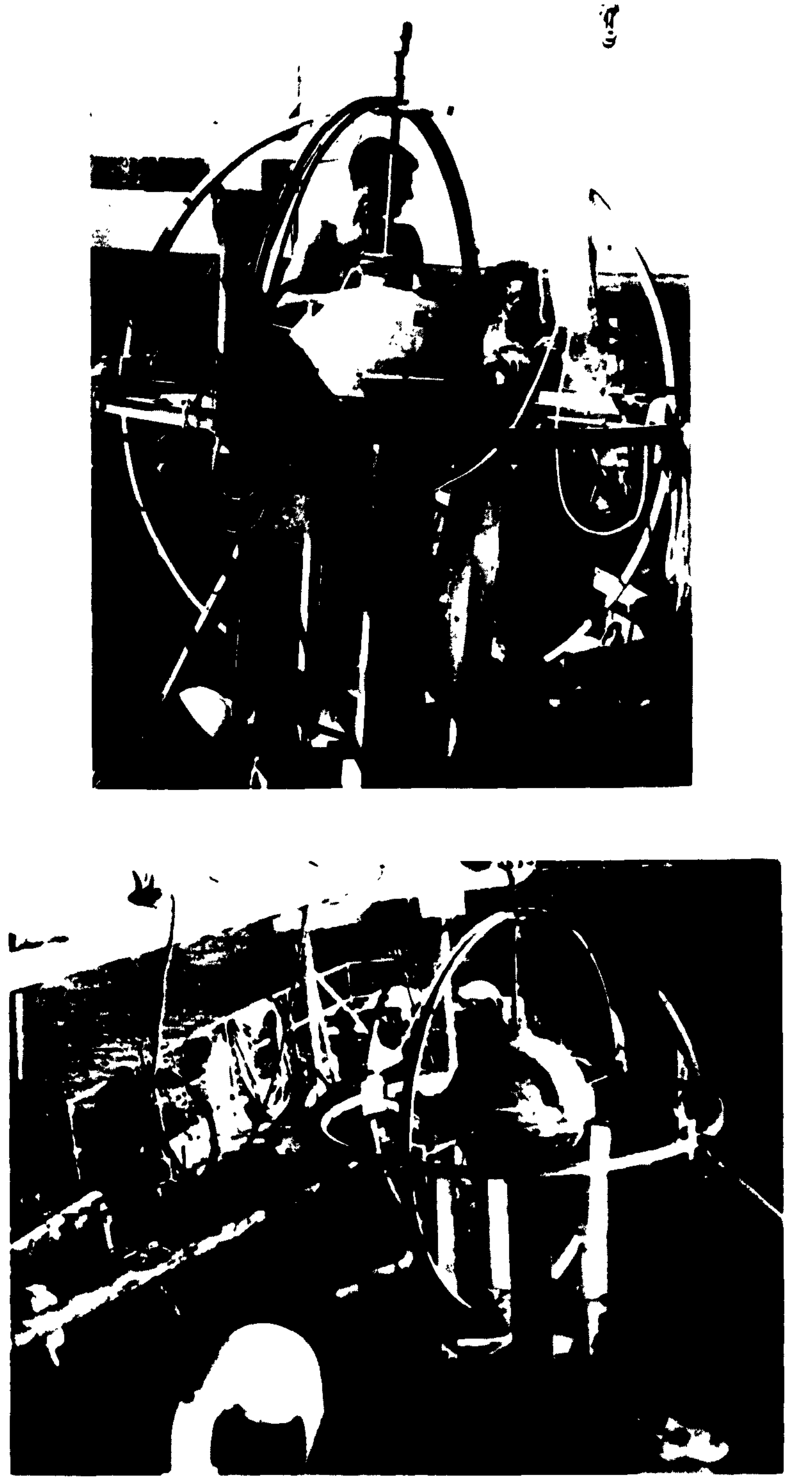

Fig. 1—Underwater aluminum sphere with three cross-loop frames

Fig. 2—Underneath sphere opened for access to recorder.

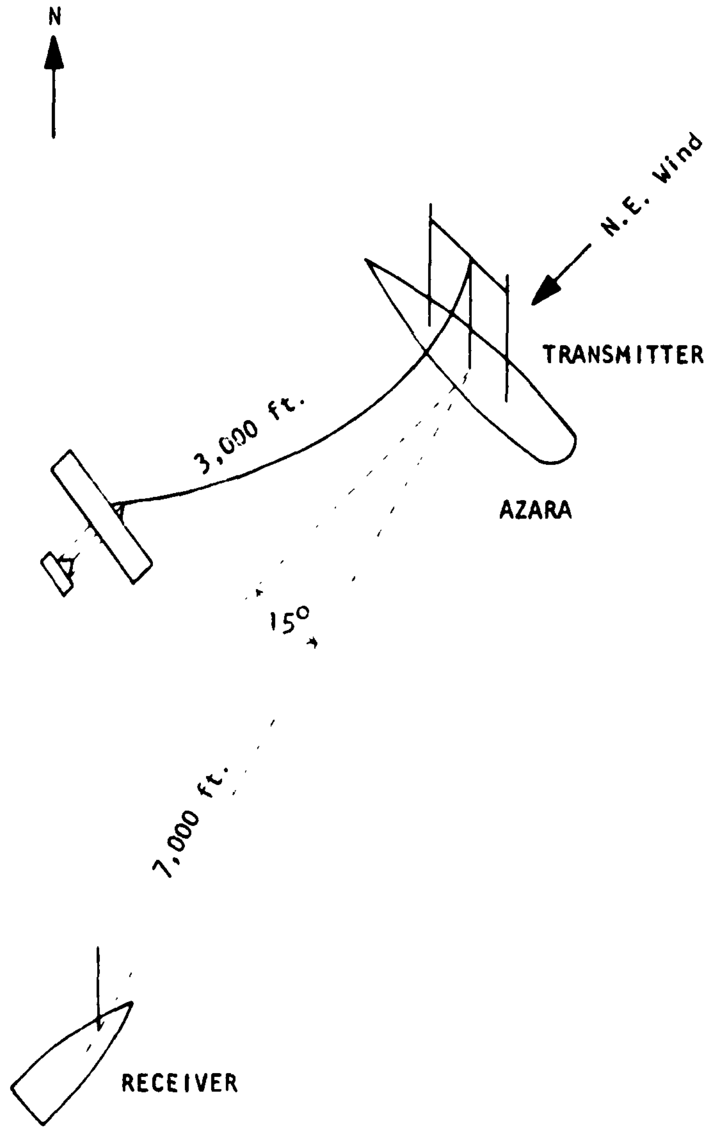

Fig. 3—Relative positions of transmitting and receiving vessels

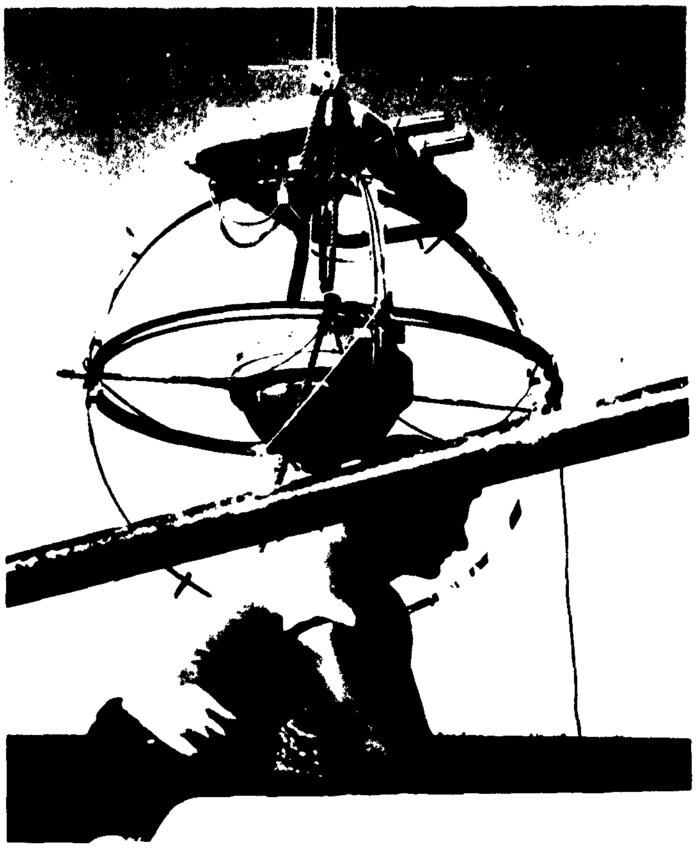

Fig. 4—Sphere with cross-loops shown suspended and also under tow.

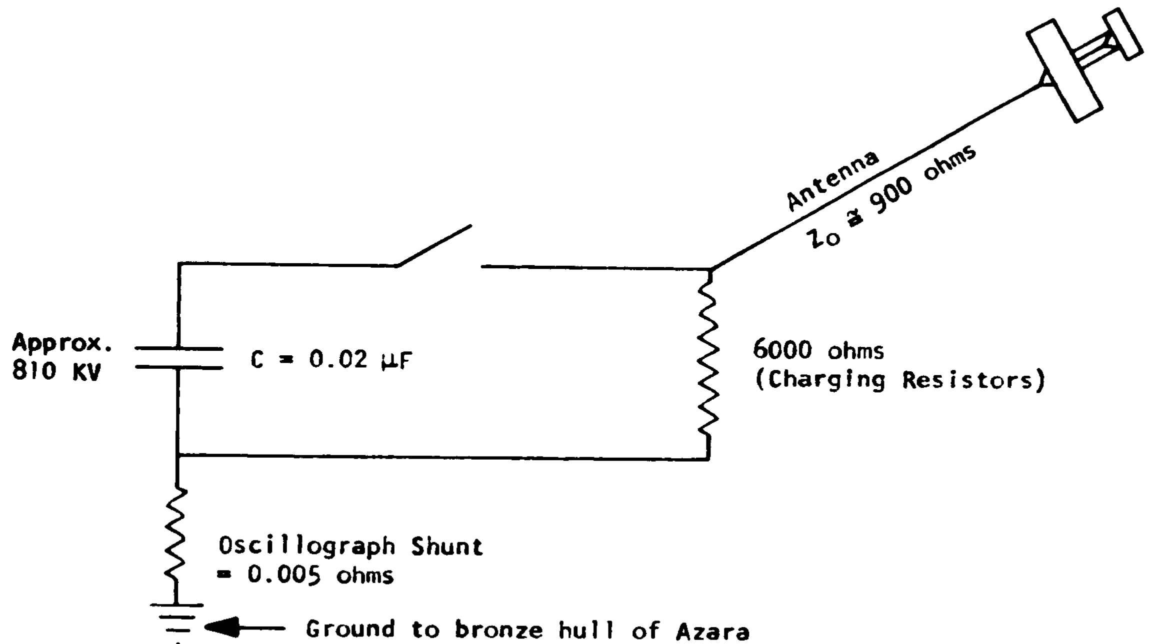

Fig. 5—Simplified equivalent circuit of transient pulse transmitter

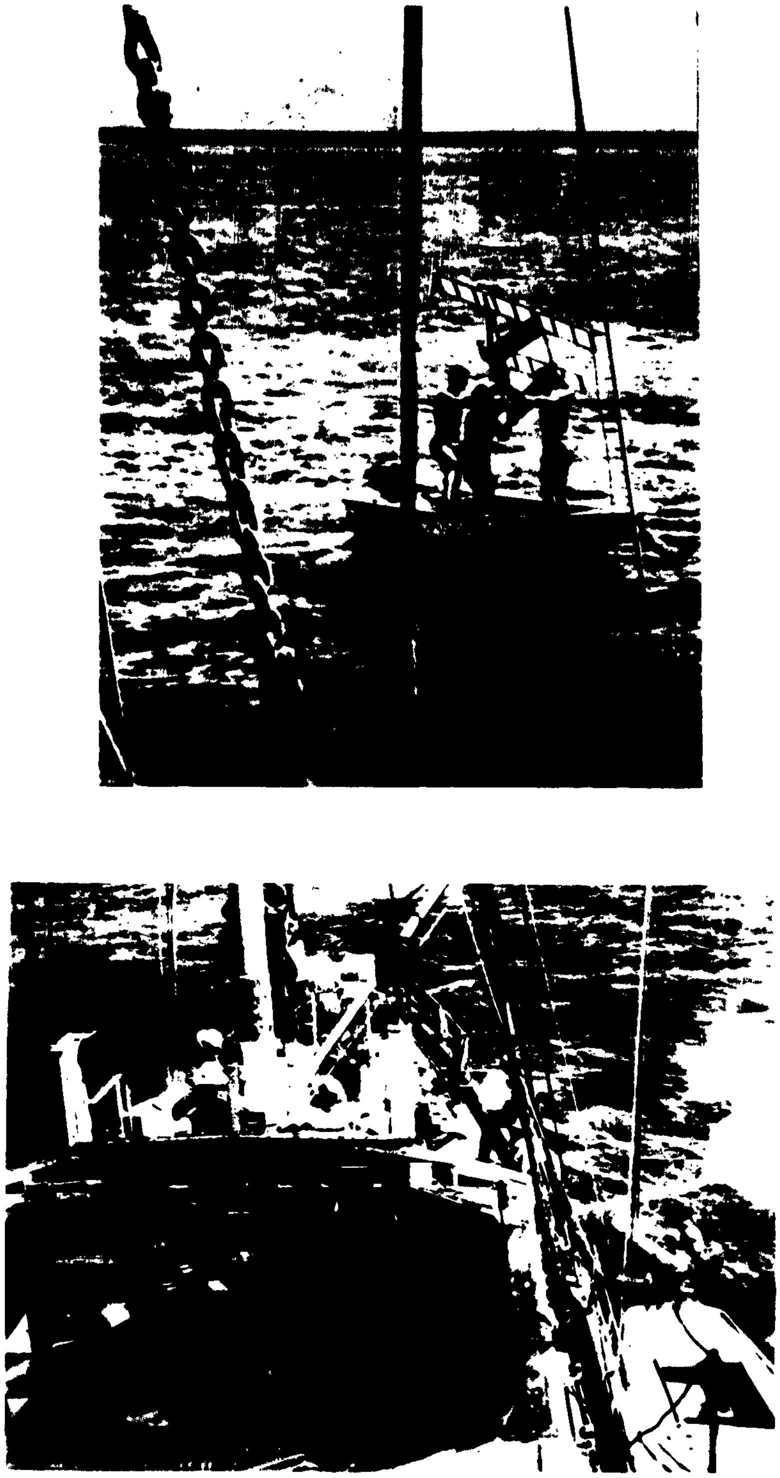

Fig. 6–View showing kite being launched and also the antenna reels above the capacitor bank.

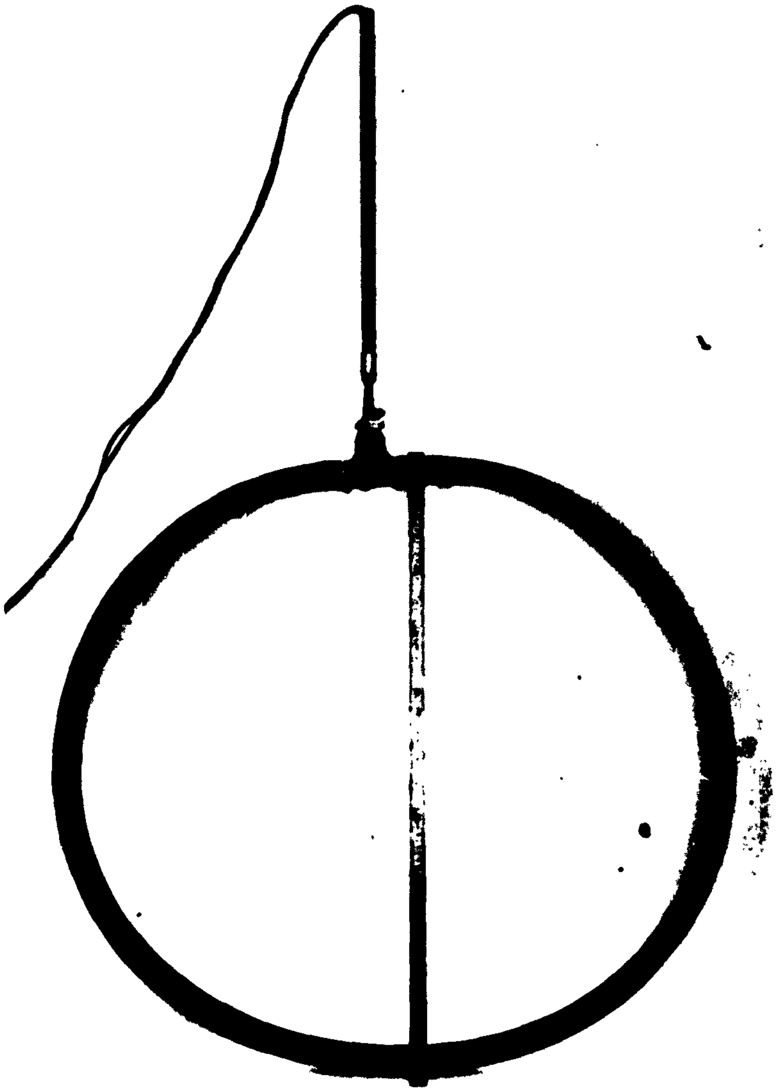

Fig. 7–Receiving loop with section of support pipe.

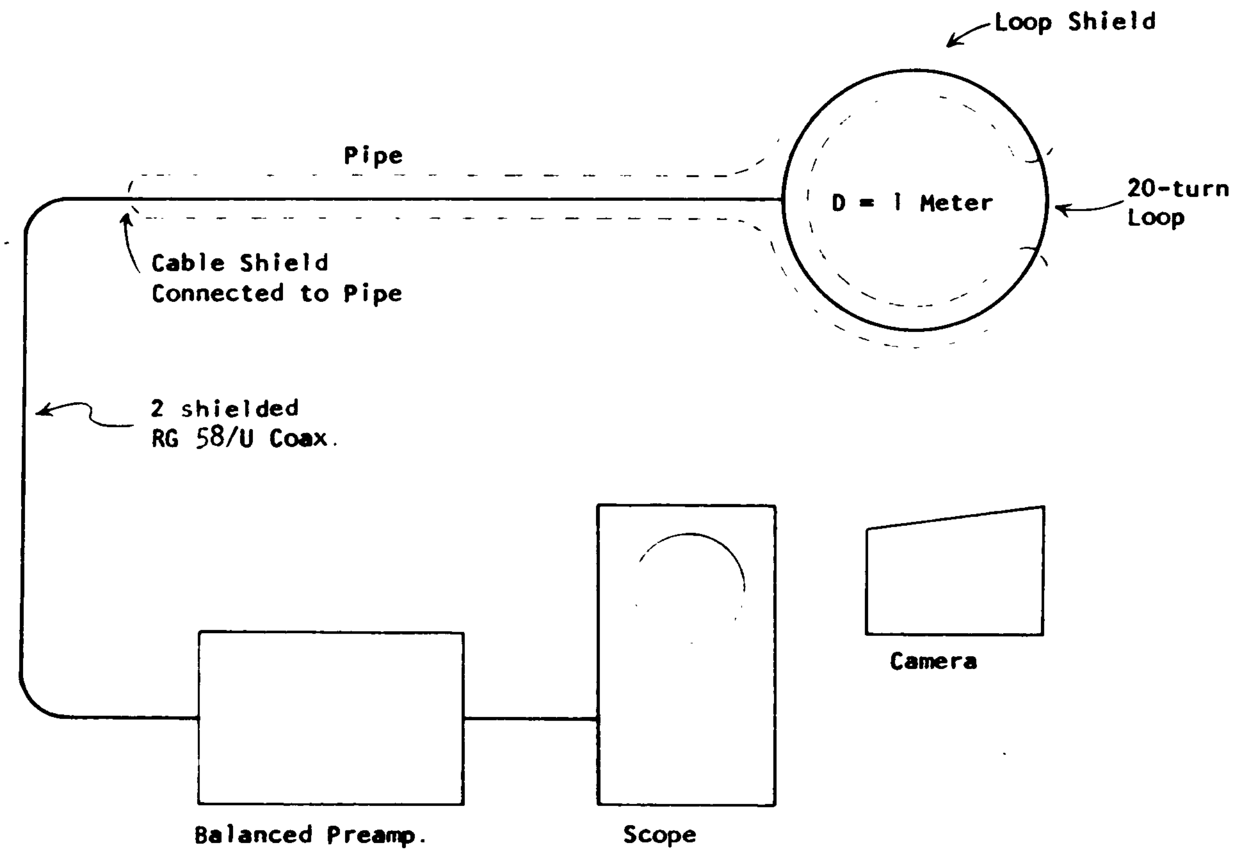

Fig. 8—Schematic of Receiving Circuit

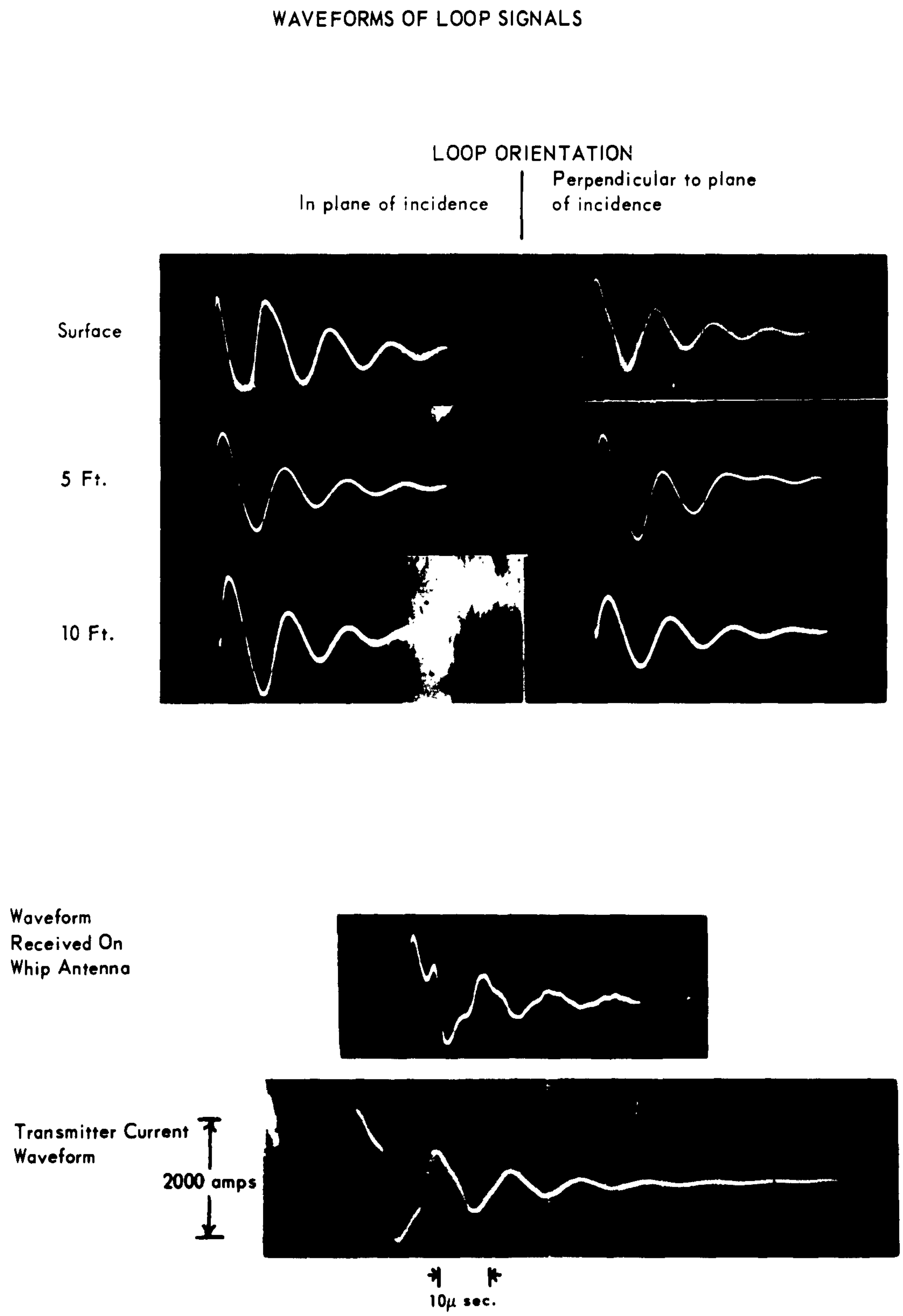

Fig. 9—Oscillograms of signals.

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